

CO detection in H₂ reducing atmosphere with mini fuel cell

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Abstract

A prototype of a miniaturized fuel cell has been studied in order to detect carbon monoxide in hydrogen-rich atmosphere for PEMFC (proton exchange membrane fuel cell) applications. It consists on a single PEMFC (membrane-electrode-assembly supplied by CEA/LITEN) directly fed by the hydrogen-carbon monoxide mixture while the cathode is exposed to ambient air. Experiments have been carried out on a laboratory testing bench with simulated reforming gas. Two working modes have been studied. For low CO concentrations (≤ 20 ppm), the amperometric mode is suitable but a regeneration in air is necessary to obtain a good reversibility of the sensor response. On the contrary, for higher CO concentrations (250–4000 ppm), a good reversible response is observed without air regenerating by using a potentiometric or quasi-potentiometric mode. Therefore, this prototype of mini fuel cell sensor seems to be convenient for monitoring reformed gases either for low temperature PEMFC which are poisoned by very low traces of CO or for high temperature PEMFC which can operate at higher CO concentrations.

Keywords:

CO detection; PEM fuel cell; Hydrogen

1. Introduction

In the field of PEMFC, CO poisoning of platinum based catalyst which is used at the anode to dissociate H₂, is now well known [1] and [2]. CO strongly adsorbs on the Pt catalyst surface, causing a decrease of the available catalytically active Pt surface area for H₂ electro-oxidation. Nevertheless, H₂ is often produced by reforming process of various fuels with an unavoidable contamination of CO. Consequently, CO sensors are very important in order to monitor the purity of the reforming gas. The difficulty to find adequate CO sensors for these fuel cell applications is related to the absence of oxygen in the gaseous flow which, besides hydrogen, contains principally carbon dioxide and water vapor.

Classical tin oxide based semiconductor sensors are not well adapted to work without oxygen because the detection principle is generally related to the reaction of reducing gas (like H₂ or CO) with the adsorbed oxygen species. Moreover, the selective detection of CO in the presence of high concentration of H₂ is difficult because ceramic gas sensors are usually more sensitive to H₂ than to CO. Only a few articles are related to the detection of reducing gases in the absence of oxygen using semiconductor SnO₂ based sensors [3], [4] and [5].

CuCl or CuBr based sensing materials have also been used with success for the CO detection in reducing gases [6]. Nevertheless, the difficulties seem to be connected to the high influence of humidity which is a key factor in fuel cell applications.

Another promising solution proposed for such application is to use mini fuel cells (solid oxide fuel cell (SOFC) or PEMFC) and to follow the degradation of the fuel cell performances due to

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the presence of CO. In the case of classical SOFC, the use of a Pd metal based anode associated with a 20 mol % Sm³⁺ – doped CeO₂ (SDC) as the electrolyte has been proposed [7]: the Pd anode was subjected to a large and reversible change in the anodic reaction resistance with the CO concentration. With the same type of material, a potentiometric sensor working with an electrode dissymmetry Au/Pt has been presented [8]: the originality of this sensor is that the two electrodes are placed in the same atmosphere without a reference cell; the difference of potential between the two electrodes (ΔV) is used as electrical signal. The response, defined by the difference between the ΔV value under carrier gas and the ΔV value under CO, is then correlated with the CO concentration (0–400 ppm). Several articles concern the use of a mini PEMFC as CO sensor for fuel applications [9], [10], [11] and [12]. For Kirby *et al.* [9], the closed cell potential of the mini PEM is a function of the current and anode polarization resulting from CO poisoning; if one further maintains the closed cell potential at a fixed value, the current through the cell becomes a single function of the CO poisoning and thereby can be used as a signal for detection. These authors show that reducing the Pt concentration of the Pt/carbon paste used for electrodes was found to increase the CO sensitivity: with a Pt/carbon paste where $[Pt] = 0.005 \text{ mg cm}^{-2}$ the measure of low CO concentration (50 ppm) could be attained within 2.5 s but air recovery is necessary to return the output current to its initial value. Mukundan *et al.* [10] use a PEM type sensor with Nafion® as electrolyte and two different metal-based electrodes which function as an amperometric sensor: one Pt electrode serves as the sensing electrode whose current density is affected by the CO adsorption whereas the other electrode, made with a Pt–Ru alloy, is quasi unaffected by the presence of CO. The sensor configuration is considerably simplified because the two electrodes are in the same atmosphere and stable response is obtained at 10–1000 ppm of CO. Planje *et al.* [11] use a two-electrodes chemical cell with a proton-conducting polymer as electrolyte: the anode (low Pt loading) is exposed to the gas flow while the cathode (high Pt loading) is immersed in water to retain the polymer conductivity. The cell cycles continuously through two potentiostatic modes, the clean-up mode ($V_{\text{anode}} > 0.6 \text{ V}$) where CO and H₂ are oxidized and the measurement mode ($V_{\text{anode}} < 0.6 \text{ V}$) where CO is only adsorbed; this sensor is able to detect CO concentrations (1–500 ppm) in H₂-rich gas mixtures. A small fuel cell fuelled by diverted stream of reformat is also used by Bhambare *et al.* [12]: in this case, the CO level is determined through time series analysis of the dynamic current response of the sensor cell due to load oscillations.

In this work, we propose to use a mini PEMFC developed by the CEA to detect CO concentrations (0–4000 ppm) in a simulated reforming gas with H₂ (5%), N₂, H₂O and eventually CO₂. Working modes have been optimized in order to detect low ($\leq 20 \text{ ppm}$) or high (up to 4000 ppm) CO concentrations.

II. Experimental

II.1. Description of the mini fuel cell sensor

The prototype used in this study has been developed by the Laboratory of Components for PEM fuel cell – Electrolysis and Modeling (LCPEM) of CEA/LITEN at Grenoble. This laboratory has a very high expertise and much experience in the field of fuel cells developments, including mini fuel cell studies. The prototype of miniaturized PEMFC contains a membrane-electrode-assembly (MEA) composed of two 1.5 cm² commercial gas diffusion electrode (BASF LT140 EWSI, 0.5 mg Pt cm⁻² loading) hot pressed at 135 °C and 4 MPa on a Nafion® 212 membrane [13]. It is a self breathing PEMFC that could be placed directly on line in the gaseous flow (anode side), while the second electrode (cathode) is simply exposed to ambient air. The prototype is presented in Figure 1. The MEA is inserted between two chambers, each of them containing a 2 mm thick porous sintered PTFE disc and a 0.5 mm thick gold mesh used as current collector.

II.2. Tests conditions

The sensor prototype has been tested on a laboratory gas bench. This bench is equipped with mass flows which allow controlling the concentrations of different gases in the carrier gas.

Hydrogen, nitrogen, carbon dioxide and carbon monoxide, pure or diluted in synthetic air, are conditioned in gas cylinders and present a high degree of purity (Alphagaz 1 quality of Air Liquide). For the present study, the carrier gas is generally a simulated reforming fuel mixture composed of H_2 diluted in N_2 (5%), with CO_2 (1.9%) and H_2O (1.8%) as additional components. The humidity level is obtained by bubbling (except CO_2) in a H_2O bottle with a thermostatically controlled temperature. The presence of moisture is essential to prevent drying of the Nafion® membrane which degrades the performance of the sensor and leads to unusable results. For security reasons during the laboratory tests, the H_2 level is limited to 5% but similar results have been obtained with higher concentrations of H_2 (up to 20% H_2 in N_2). The concentration of O_2 in the gas mixture, measured by various O_2 probes, is still less than 50 ppm. Two different ranges of CO concentrations have been studied. One (from 2.5 to 20 ppm) concerns particularly the normal low temperature PEMFC which are poisoned by low traces of CO, and the other (from 250 to 4000 ppm or more) is representative of reforming gas and well adapted to the monitoring of high temperature PEMFC that are resistant to higher levels of CO. The control of the test bench is provided by the Labview software. Finally, all tests were performed at room temperature in the range 20–25 °C.

The miniaturized fuel cell has been built with two 1/4" gas tubes: these tubes are connected to the anode side and are used for the inlet and outlet of the reforming gas. The second chamber of the sensor (cathode side) is equipped with a metal grid allowing the contact of the cathode directly with the ambient air.

In the case of classical experiments, the signal from the mini PEMFC is first stabilized in the carrier gas and injections of increasing concentrations of CO are performed. Each injection is followed by an exposure to the carrier gas of varying duration that depends on the reversibility of the phenomenon. If the initial value is not recovered, the carrier gas is replaced by pure synthetic air in order to regenerate the sensor. The gas flow is maintained at 6 l h⁻¹ throughout the test.

As with conventional fuel cells, different working modes can be proposed. On one hand, an external loading resistor (R) can be placed in the electrical circuit. The value of R varies between 1 and 10⁶ Ω. In these so-called amperometric (for $R \leq 10^3 \Omega$) or quasi-potentiometric (for values of $R \geq 10^4 \Omega$) modes, the ongoing performances of the mini PEMFC (voltage, current and possibly power) are followed depending on the nature of gas and in particular the presence of CO in the reformat. On the other hand, the open circuit voltage (OCV) which corresponds to the maximum voltage delivered by the cell is measured at zero current (without load resistor): this mode of operation is the so-called potentiometric or OCV mode. Results of the electrical measurements have been obtained by a data acquisition system by using the Deloger software.

III. Results

III.1. Amperometric mode

The first experiments were conducted with amperometric mode by using low load resistors. For a value of load resistor of 10 Ω, the cell voltage (ΔV) developed at the terminals of the mini PEMFC is around 530 mV. When a level of 50 ppm of CO is introduced into the gas mixture, the value of ΔV falls sharply to approximately 75 mV. After removal of CO, the signal does not reach its original value even after 3 h. The entire reversibility can be achieved only by regeneration in air, *i.e.* replacing the carrier gas by pure synthetic air. These results are shown in Figure 2 with a period of air recovery of 1 h. We will see later that the period of regeneration may be reduced to 5 min or less (about 1 min).

Similar results are obtained with load resistors of less than 10 Ω. The results reported in Figure 3 are obtained with a load resistor of 1 Ω and CO levels ranging between 2.5 and 20 ppm. In this case, the initial value of ΔV before the injection of CO is close to 60 mV. We see first that the signal appears very quickly saturated because the value of ΔV drops to only a few mV at 10 ppm CO. In addition, the reversibility after 1 h in the absence CO is very poor and this leads to a progressive decrease in the ability to detect increasing injections of CO with this operating mode (see Figure 3a). However, if a regeneration of 5 min (or less) in air is

performed, we find that ΔV recovers its original value before the next injection of CO (see Figure 3b). Under certain experimental conditions, it is nevertheless possible to follow changes in CO content around a mean value without any air regenerating (as it will be mentioned later in Section IV).

Some experiments were also conducted with the load resistor higher than 10 Ω . The results obtained for a load resistor of 1000 Ω are shown in Figure 4. Firstly, we note that the initial value of ΔV is, as expected, much higher than in the previous cases since it is close to 700 mV. Furthermore, we see that the reversibility of the signal is almost complete 1 h after removing the CO gas flow. The regeneration step under air did not seem absolutely necessary in this case.

Moreover, increasing the load resistor decreases CO response but also increases the response time. In some cases (low CO content and/or high load resistance), the total response is still not obtained 1 h after the injection of CO (see Figure 3 and Figure 4). To obtain quantitative information, the relative response R_r (expressed in percent) is represented by the following expression:

$$R_r = \left(\frac{|\Delta V_{t=1h} - \Delta V_{t=0}|}{\Delta V_{t=0}} \right) \times 100\% \quad (1)$$

where $\Delta V_{t=0}$ and $\Delta V_{t=1h}$ represent the values of ΔV at the time of injection of CO and 1 h after CO exposure, respectively. According to the definition of R_r and taking into account that $\Delta V_{t=1h}$ is less than $\Delta V_{t=0}$, the maximum value of R_r is obviously equal to 100. The results obtained for the levels of CO between 0 and 20 ppm and for values of load resistor between 1 Ω and 1000 Ω are shown in Figure 5. By the way of comparison (see below), the observed results without load resistor (potentiometric (or OCV) mode) are also plotted on this Figure 5. On one side, we confirm that the relative response appears very quickly saturated (from 10 to 20 ppm CO) for low values of load resistor (1 or 10 Ω). On the other side, in the case of a high load resistor (1000 Ω for example), there is only a 20% response for 20 ppm CO, which augurs the possibility of detecting higher levels of CO. However, the use of a low load resistor (*e.g.* 10 Ω) can be interesting to very quickly detect (in the case of alarm threshold for example) a high CO content (*e.g.* 1000 ppm) because the measured response time is then short (about 30 s for 50% response) as shown in Figure 6.

III.2. Quasi-potentiometric and potentiometric modes

If the load resistor increases more (10^4 – 10^6 Ω), the supplied current is very low and the value of ΔV tends to a value close to 800–900 mV: this operation mode is so-called quasi-potentiometric mode. In the absence of load resistor, the value of ΔV becomes equal to the open cell voltage (OCV): this operation mode is so-called potentiometric mode. As assumed above, these modes lead to a sensor able to detect high levels of CO.

The results for CO concentrations ranging between 250 and 4000 ppm and for values of load resistor of 10^4 Ω and 10^6 Ω are reported in Figures 7a and b, respectively. In both cases, the injection of high levels of CO in the simulated reformat is reflected by large responses of the mini PEMFC. Furthermore the reversibility is virtually complete in a reasonable period of time and a step of regeneration in pure air does not seem absolutely necessary. Moreover, the value of ΔV obtained under high levels of CO remains almost stable during long-term injection (see Figure 7b, in the case of an injection of 4000 ppm CO for a period of 5 h).

For the potentiometric mode, the results obtained for low levels of CO (between 2.5 and 20 ppm) confirm the low sensitivity of the device (see Figure 5). However, as in the case of the quasi potentiometric mode, this mode is useful for the detection of higher levels of CO: the results for CO concentrations ranging between 250 and 4000 ppm are reported in Figure 8. By the way of comparison, the obtained results with 20% H_2 are also plotted on this Figure 8: it could be noticed that results are quite similar for 5 and 20% H_2 , but with a shorter response time for the higher H_2 content, especially for lower levels of CO (≤ 500 ppm).

IV. Discussion

The cell voltage (ΔV) is equal to the difference between the electrical potential V_c of the cathode and the electrical potential V_a of the anode.

At the anode, the following reaction takes place:



The protons then migrate through the Nafion[®] membrane to the cathode where the following reaction takes place:



The overall reaction is then:



In the case of open circuit voltage (potentiometric mode), V_c is close to 1 V ($E_{\text{O}_2/\text{H}_2\text{O}}^0 = 1.23\text{V}$ vs. SHE) while V_a is equal to 0 V ($E_{\text{H}^+/\text{H}_2}^0 = 0\text{V}$ vs. SHE), $E_{\text{oxidant/reducer}}^0$ being the standard potential.

The value of the cell voltage is then close to 1 V. As soon as the mini PEM delivers a current, this value decreases due to various phenomena such as the ohmic losses across the electrolyte material and the electrode over potentials. It can thus be observed that the value of the cell voltage, of about 920 mV in the case of the potentiometric mode (see Figure 8), decreases slightly (870 mV) for a load resistor of $10^6 \Omega$ (see Figure 7b). When the current increases, this effect becomes more significant as the value of the cell voltage is close to 530 mV and 60 mV for values of load resistance of 10Ω and 1Ω , respectively (see Figure 2 and Figure 3). Another reason which may lead to a decrease in the cell voltage is the presence of CO in the gas stream. Indeed, at the anode, the CO adsorbs strongly on the platinum on the same sites as H_2 , which increases the effective current density and the anode polarization [14]: this leads to a decrease in cell voltage. In fact, this effect allows this mini PEM behave as a true CO sensor as shown in Figure 2, Figure 7 and Figure 8 as for example.

Based on the results above presented, it seems that the detection performances are widely dependent on operating mode.

For low values of R ($10 \leq R \leq 100 \Omega$), the supplied current by the mini PEM (amperometric mode) is relatively large (up to 50 mA) and the cell voltage ($V_c - V_a$) is of the order of 500 mV: in this case, there is a high relative response of the device since CO levels as low as 2.5 ppm can be easily detected (see Figure 5). The effect of adsorbed CO results in a rapid decrease in cell voltage whose value drops to a value of 100 mV or less. Under these conditions, the kinetics of the response is very fast (except for CO levels less than 10 ppm) since a response time (50% response) of 30 s is measured in the case of a load resistor of 10Ω and a CO concentration of 1000 ppm (see Figure 6b).

If, on the contrary, a large value of R ($10^4 \leq R \leq 10^6 \Omega$) is selected, the supplied current by the mini PEM is very low (quasi-potentiometric mode); it becomes zero in the absence of load resistor (potentiometric mode). In both modes, the value of the initial cell voltage is high: it is equal to 750 mV or 920 mV for $R = 10^4 \Omega$ (see Figure 7a) or in the case of the potentiometric mode (see Figure 8), respectively. Moreover, the relative response decreases sharply (see Figure 5 in the case of the potentiometric mode) and CO levels below 20 ppm are very difficult to detect. However, levels of CO between 250 and 4000 ppm (or more) lead to large responses (see Figure 7 and Figure 8). For 250 ppm CO the response time is quite long but it decreases for higher CO concentrations: it is of the order of 75 s (50% response) in the case of the potentiometric mode and for a CO content of 1000 ppm (see Figure 8).

Regarding the reversibility of the response, it may take place by oxidation or simply by desorption of adsorbed CO. The oxidation of CO can occur in the presence of water according to the following reaction:



and results in an increase of the cell voltage related with the decrease of the anode polarization. However, this reaction is only possible if the anode potential V_a is higher than 600 mV vs SHE [11] and [15].

In the case of amperometric mode ($10 \leq R \leq 100 \Omega$) the cell voltage ($V_c - V_a$) drops to an average of 500–600 mV in the absence of any trace of CO; this drop is largely due to the cathode over voltage [16] since the anode polarization is negligible under these conditions of cell operation. Assuming, like Kirby *et al.* [9], the cathode potential V_c does not vary too much whatever the CO concentration in the anodic gas supply, it follows that the difference: $(V_c - V_a)_{\text{before CO injection}} - (V_c - V_a)_{\text{after CO injection}}$ is representative of the final value of V_a (under CO pollution). It could be noticed that V_a remains well below 600 mV under CO pollution: for example, it is of the order of 460 mV for $R = 10 \Omega$ and a CO content of 50 ppm (see Figure 2). When CO is removed, it could not be oxidized and the signal recovers very slowly its original value without air regenerating. However, in some cases, the value of the anode potential V_a under CO pollution is closer to 600 mV (see Figure 6 in which V_a is of the order of 500 mV for $R = 10 \Omega$ and a CO content of 1000 ppm): when CO is removed from the gas stream, the return to baseline then occurs in two steps. This phenomenon is clearly visible in Figure 6a. The first step is very fast, results in an increase in the value of the cell voltage up to 400 mV and is possibly followed by oscillations; the second one is much slower and may require a period of several hours to obtain the almost complete reversibility of the signal. During the first stage, there is likely the oxidation of CO by reaction (5); the possible oscillations depend on the CO content and intensity of supplied current and are probably related to oxidation–reduction phenomena commonly encountered in devices such as PEM involving CO and Pt in reducing atmospheres at low temperatures [14]. During the second stage, the value of the cell voltage increases and V_a falls below 300 mV, which no longer allows easy oxidation of CO; the reversibility of the signal is then mainly ensured by the slow desorption of CO and air regenerating is requiring. Nevertheless, as can be seen in Figure 9, if the value of the cell voltage remains sufficiently low, the monitoring of changes in CO levels seems possible both in the sense of increasing levels and for decreasing levels: changes in the CO content of about 25–100 ppm around a mean value of 100 ppm are thus easily and rapidly (about 10 s for 100% response) detectable.

When the current supplied by the mini PEMFC is still more important (see Figure 3 for $R = 1 \Omega$) these observations remain largely the same. However, the polarization of both electrodes becomes more important, even without any CO in the anode gas feeding.

In the case of quasi-potentiometric or potentiometric modes, the value of the initial cell voltage is usually between 750 and 920 mV, respectively (see Figure 7 and Figure 8). It can be observed that even for significant levels of CO (*e.g.* 4000 ppm), the value of the cell voltage remains above 300 mV (see *e.g.* Figure 7a ($R = 104 \Omega$)) or 650 mV (see *e.g.* Figure 8 (potentiometric mode)). It is therefore reasonable to assume that in both cases the potential V_a of the anode is less than 450 mV which does not allow an easy oxidation of CO according to the reaction (5). That is why the return to baseline after CO removal occurs in one step probably corresponding to a simple desorption of CO. In this case, the air regeneration does not seem necessary because the time to return to the baseline is relatively acceptable (less than 30 min). Several experiments are currently carried out by changing the load resistor value during the recovery stage: it can be shown that CO desorption is complete only four hours after CO removing. In fact, the sensor response seems to be completely reversible in a much shorter time because of the low sensitivity of the sensor under these operating conditions (quasi-potentiometric or potentiometric modes). It is likely that air regenerating will be required in the case of long exposures under high CO levels.

These various explanations have been given in order to interpret the observed phenomena. Further experiments are obviously required to explain more thoroughly the results presented here and particularly the shape of the curves obtained during the return to baseline after removal of CO. Moreover, the performances of such a sensor under various operating modes

and for CO levels between 2.5 and 4000 ppm have been relatively satisfactory during three months. However, long-term experiments are obviously needed to assess more precisely the stability of the device.

V. Conclusions

In this study, the CO detection performances of a mini PEMFC were evaluated on a test bench. This device is a self breathing PEMFC that could be placed directly on line in the gaseous flow (anode side), while the second electrode (cathode) is simply exposed to ambient air. The carrier gas is a simulated reforming fuel mixture composed of H₂ diluted in N₂ (5%), with CO₂ (1.9%) and H₂O (1.8%) as additional components. Different operating modes have been considered. With load resistor (R) placed in the external circuit the evolution of the closed cell potential is recorded: this mode is so-called amperometric in the case of low values of R ($1\ \Omega < R < 10^3\ \Omega$) and quasi-potentiometric in the case of high values of R ($10^4\ \Omega < R < 10^6\ \Omega$). In the absence of load resistor, the cell voltage takes the value of open cell voltage (OCV): this is the so-called potentiometric mode. The obtained results depend on the selected mode.

In the case of amperometric mode, the device has a high sensitivity since levels of about 2.5–20 ppm can be easily detected. When the CO content increases, the relative response appears very quickly saturated but the response time (50% response) becomes very interesting (*e.g.* 30 s for 1000 ppm CO). Nevertheless, under this operation mode, a recovery in pure air is absolutely necessary to fully desorb the CO which leads to discontinuous operation of the sensor.

In the case of potentiometric or quasi-potentiometric modes, the relative response is much lower and high levels of CO (up to 4000 ppm or more) are easily detectable. The response time is slightly longer than in the case of amperometric mode; moreover, the reversibility of the response is almost complete and the stage of regeneration under pure air did not seem necessary that allows continuous operation of the device.

In the case of a low temperature PEMFC for which CO poisoning is critical, an amperometric mode seems preferable with a periodic regeneration in pure air.

For high temperature PEMFC, the CO poisoning is less severe and it seems that potentiometric or quasi-potentiometric are suitable modes for continuous operation. A detection system using two mini PEMFC sensors could also be considered. The first, operating in amperometric mode ($R = 10\ \Omega$ for example), would be useful to quickly detect the presence of CO in the reformat (alarm threshold). The second, operating in quasi-potentiometric mode ($R = 10^5$ or $10^6\ \Omega$ for example), would be interesting to determine more precisely the CO concentration; when the return to baseline has been achieved and thus the CO pollution has disappeared, it could start the regeneration step of the first sensor.

The goal of current research is to improve the knowledge of encountered mechanisms in order to explain in more detail some observed phenomena such as the shape of the curves during the return to baseline.

Acknowledgments

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Figures

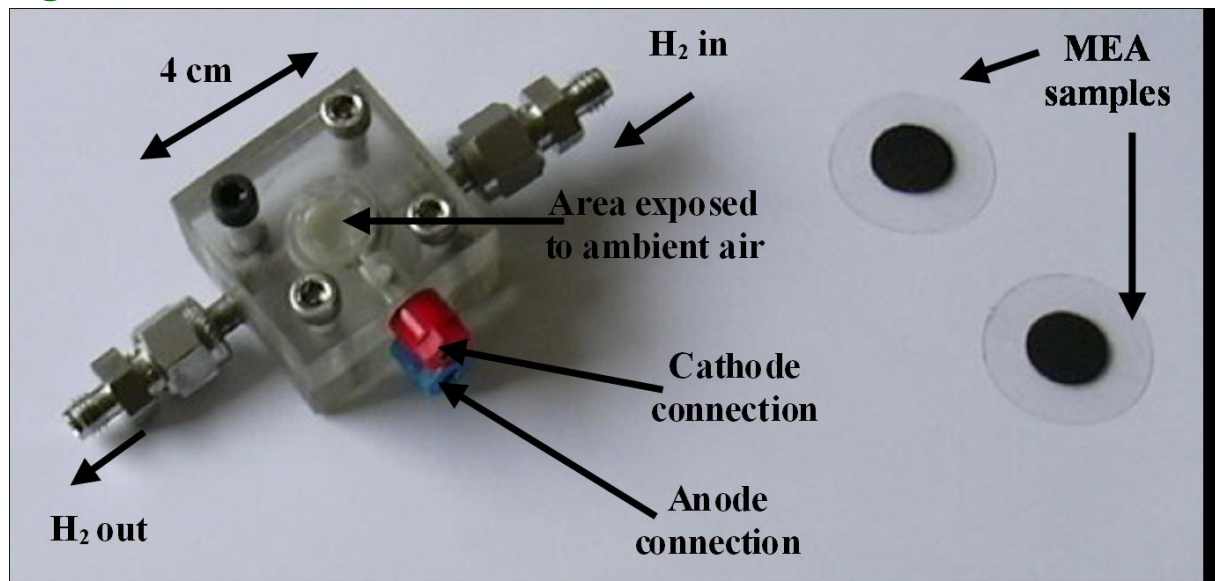


Figure 1: Prototype of mini fuel cell.

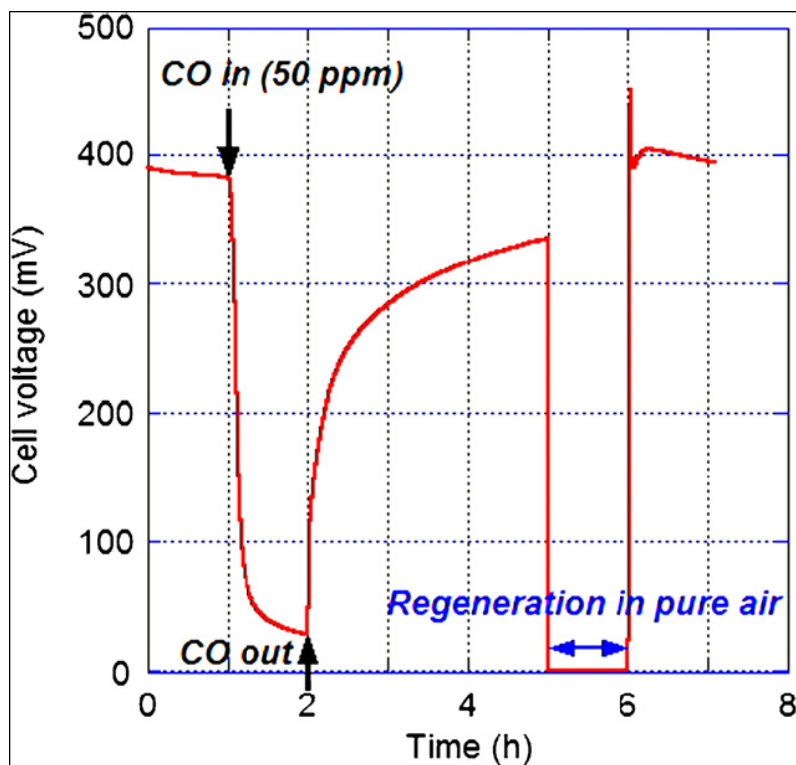


Figure 2: Response of the fuel cell to 50 ppm CO with a step of regeneration in pure air. Carrier gas: $[H_2] = 5\%/N_2$ with $[H_2O] (1.8\%)$ and $[CO_2] (1.9\%)$. Amperometric mode: $R = 10 \Omega$.

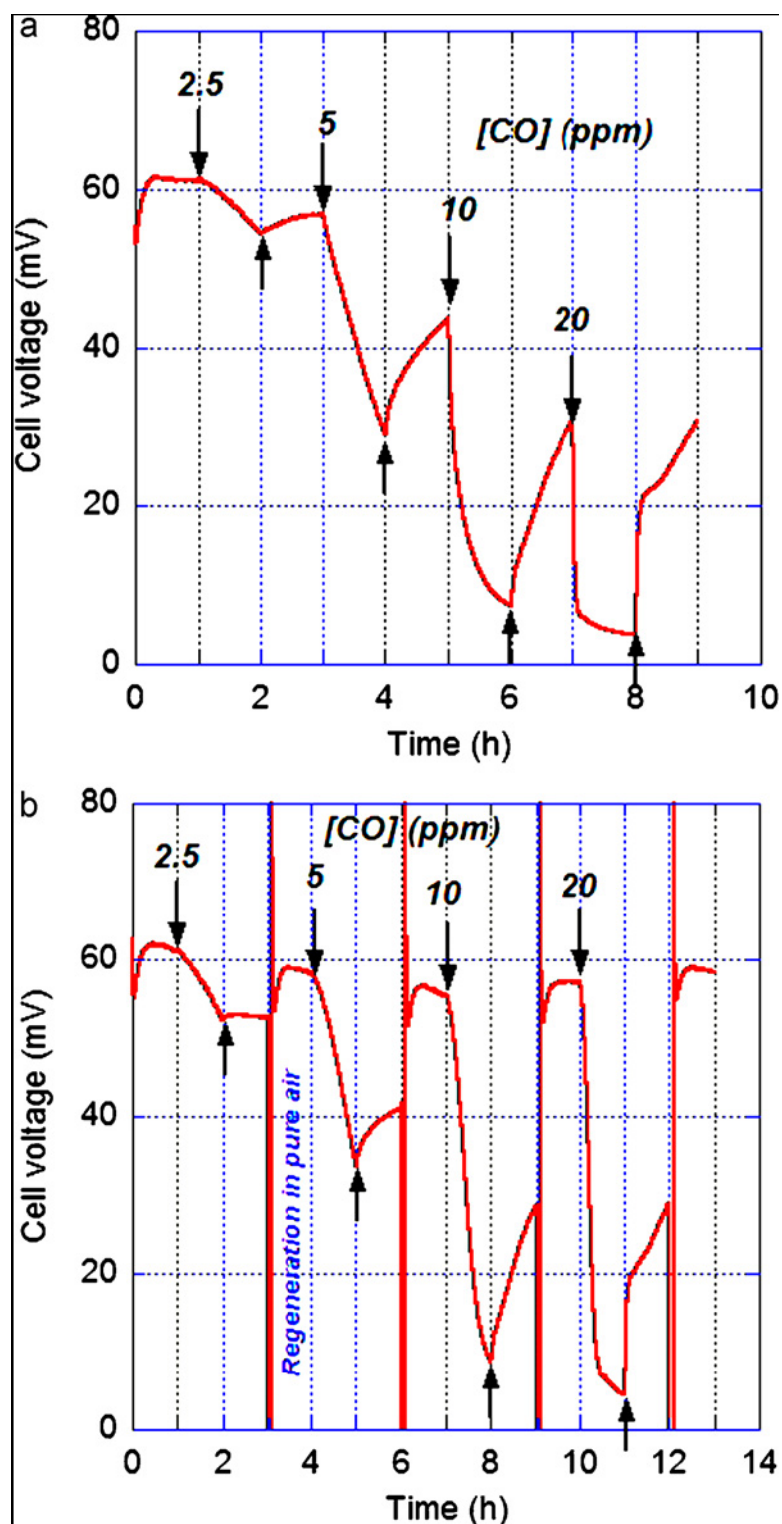


Figure 3: Response of the fuel cell to injections of CO from 2.5 to 20 ppm. Carrier gas: $[H_2] = 5\%/N_2$ with $[H_2O]$ (1.8%) and $[CO_2]$ (1.9%). Amperometric mode: $R = 1 \Omega$. (a) Without regeneration in pure air; (b) with regeneration in pure air after each CO injection.

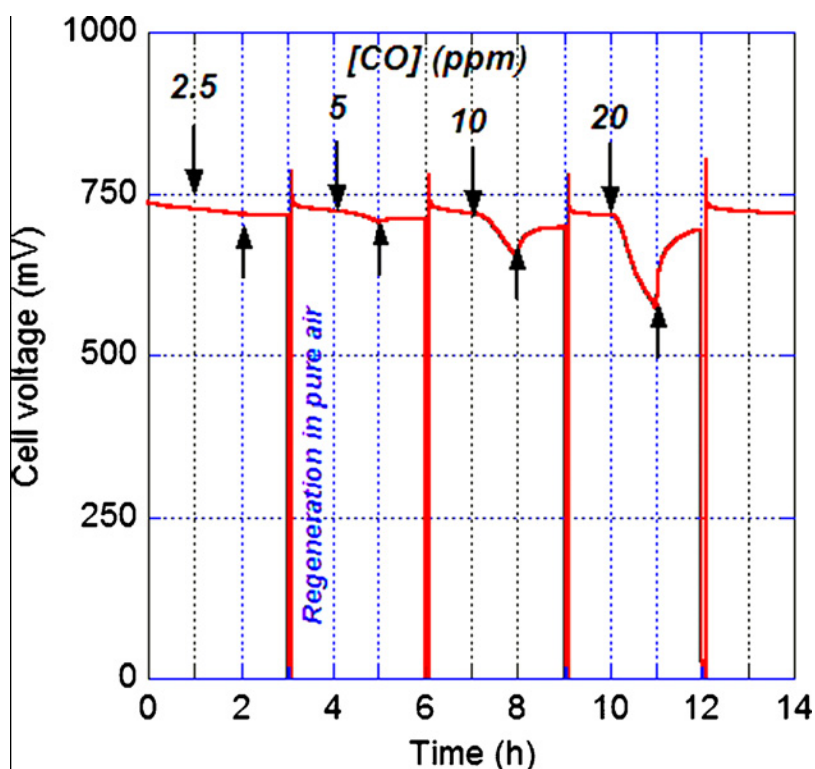


Figure 4: Response of the fuel cell to injections of CO from 2.5 to 20 ppm. Carrier gas: $[H_2] = 5\%/N_2$ with $[H_2O]$ (1.8%) and $[CO_2]$ (1.9%). Amperometric mode: $R = 10^3 \Omega$; regeneration in pure air after each CO injection.

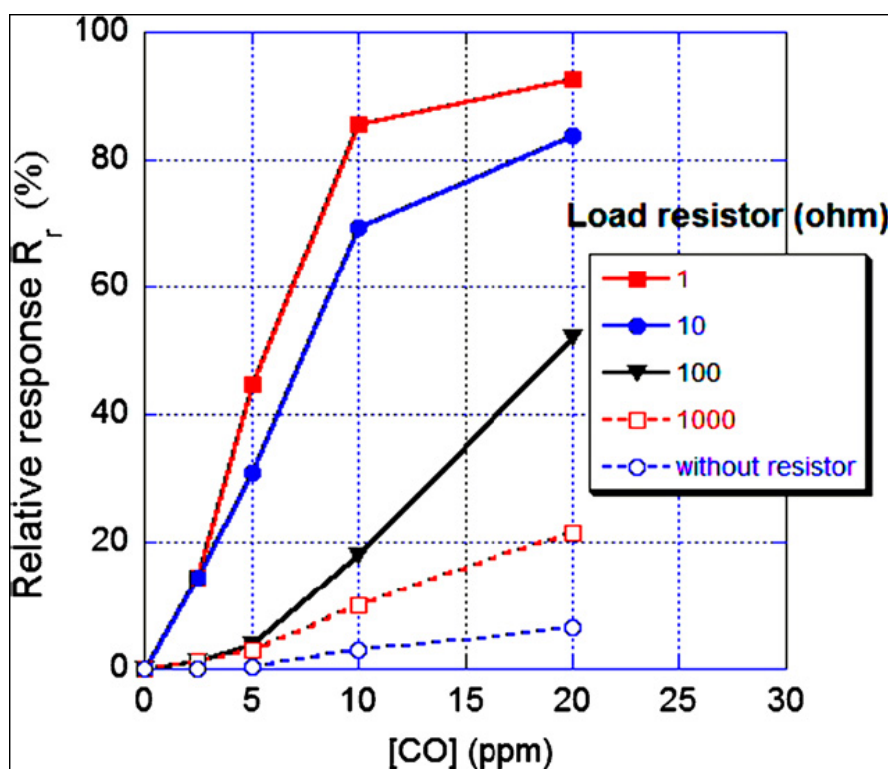


Figure 5: Relative response R_r of the fuel cell as a function of CO content (0–20 ppm) for several values of load resistor.

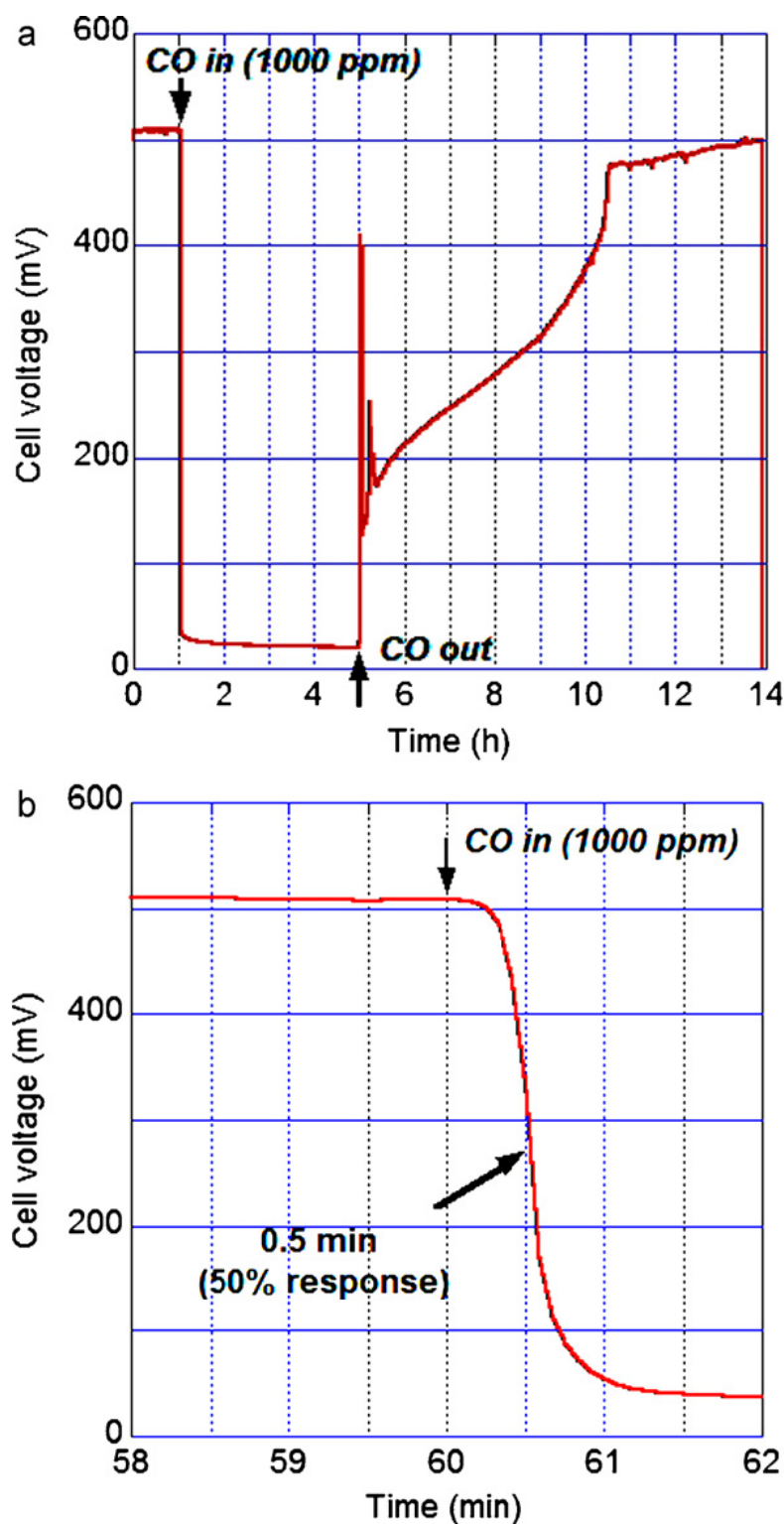


Figure 6: Response of the fuel cell to 1000 ppm CO without regeneration in pure air. Carrier gas: $[H_2] = 5\%/N_2$ with $[H_2O] (1.8\%)$ and $[CO_2] (1.9\%)$. Amperometric mode: $R = 10 \Omega$. (a) transient response and recovery step; (b) details of the response.

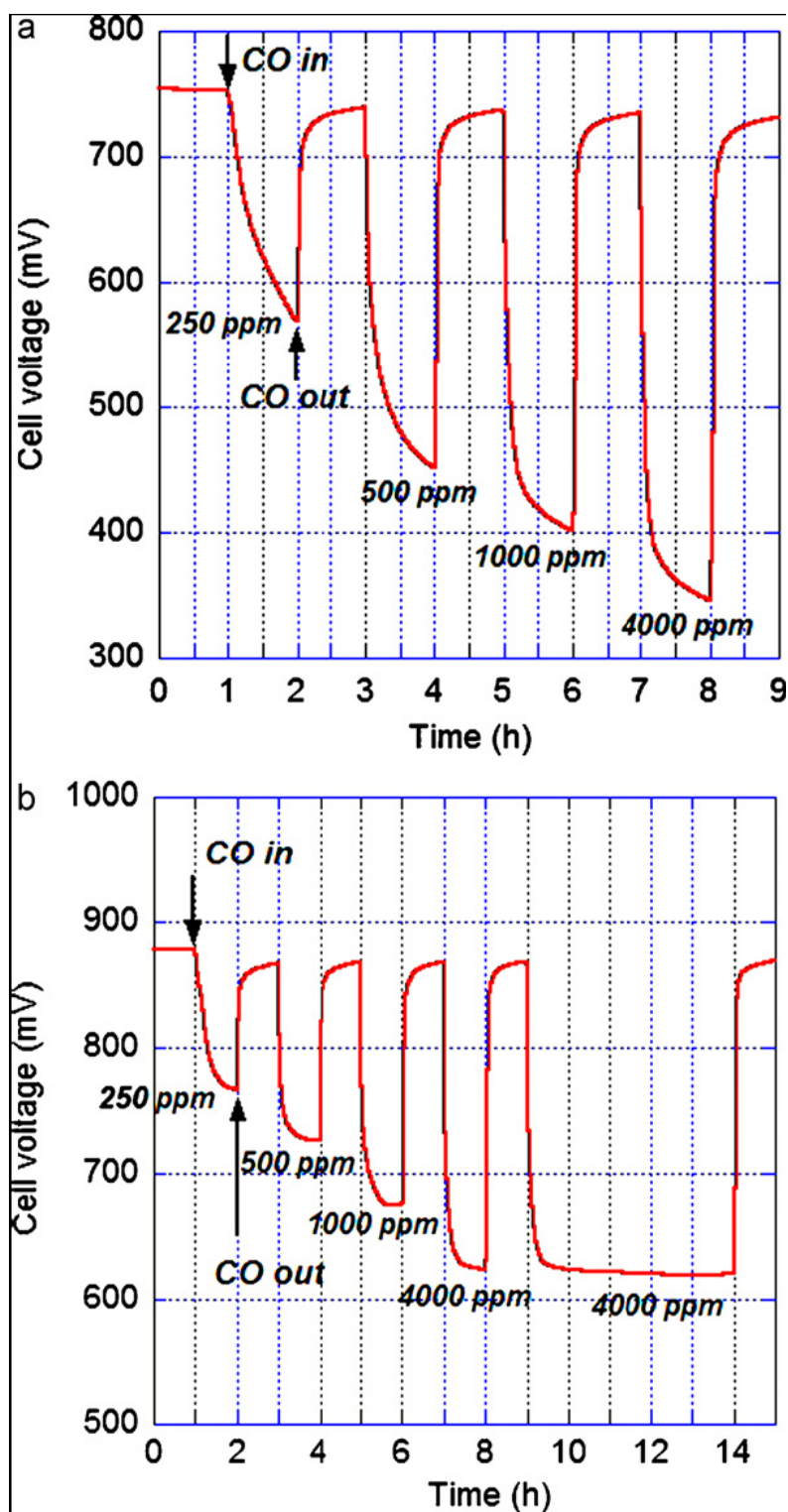


Figure 7: Response of the fuel cell to injections of CO from 250 to 4000 ppm. Carrier gas: $[H_2] = 5\%/N_2$ with $[H_2O] (1.8\%)$ and $[CO_2] (1.9\%)$. Quasi potentiometric mode. (a) $R = 10^4 \Omega$; (b) $R = 10^6 \Omega$.

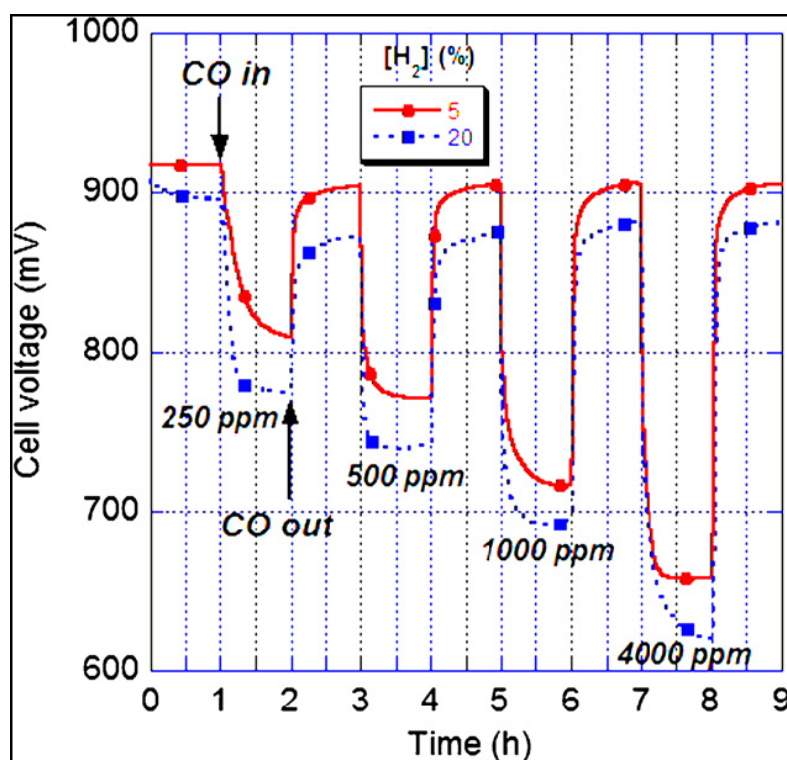


Figure 8: Response of the fuel cell to injections of CO from 250 to 4000 ppm. Carrier gas: $[H_2] = 5$ or $20\%/N_2$ with $[H_2O]$ (1.8%) and $[CO_2]$ (1.9%). Potentiometric mode.

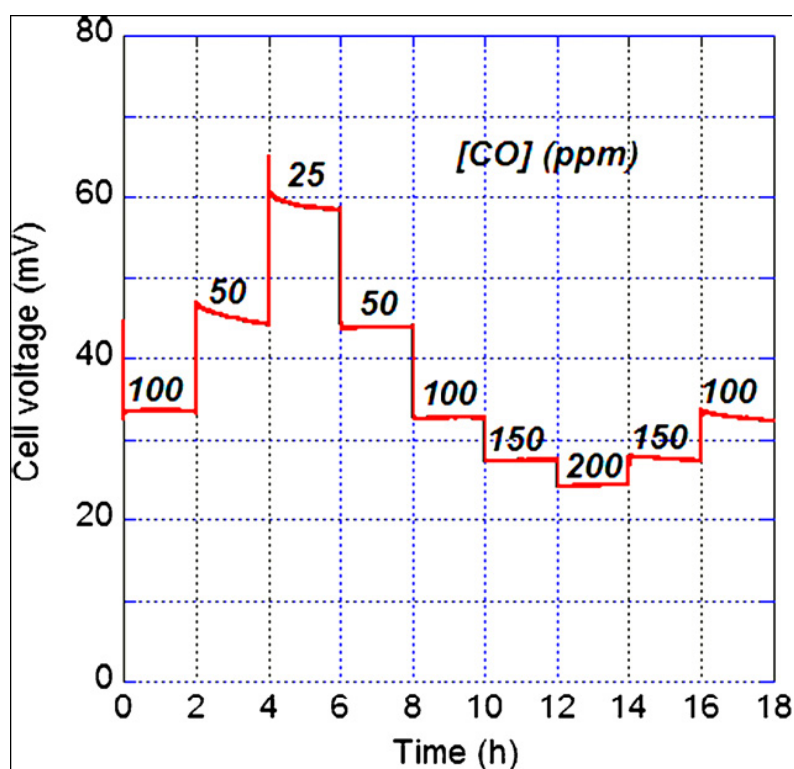


Figure 9: Evolution of the cell voltage of the fuel cell for changes in the CO content in the range 25–200 ppm. Carrier gas: $[H_2] = 5\%/N_2$ with $[H_2O]$ (1.8%), $[CO_2]$ (1.9%) and $[CO]$ (100 ppm). Amperometric mode: $R = 10 \Omega$.